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14. ABSTRACT This paper compares evening sector measurements by the Jicamarca unattended long-term studies of the ionosphere and atmosphere (JULIA) radar, the Ancon scintillation monitor, and plasma density sensors on Defense Meteorological Satellite Program (DMSP) satellites. During more than half of the 110 nights of JULIA operations in 1998 and 1999, backscatter was observed from plumes extending above the layer of bottomside spread F. On 98% of the nights with no plumes, the S_4 index measured at Ancon was <0.8. On ~90% nights with plumes, $S_4 \geq 0.8$. DMSP F14 crossed the magnetic equator within 7.5 deg longitude of Ancon near the 2100 local time (LT) meridian on 61 nights. During 32 overpasses, DMSP detected no equatorial plasma bubbles (EPBs) and JULIA detected no plumes. DMSP encountered EPBs on only 9 of the remaining 29 nights when JULIA observed plumes. Two plumes detected by JULIA on 15 Apr 99 did not coincide with nearby EPBs crossed by the two satellites on the same evening. We compared the seasonally average percent of nights with $S_4 > 0.8$ at Ancon with the percent of orbits in which a DMSP satellite detected EPBs..

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Multipoint observations of equatorial plasma bubbles

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[1] This paper compares evening sector measurements by the Jicamarca unattended long-term studies of the ionosphere and atmosphere (JULIA) radar, the Ancon scintillation monitor, and plasma density sensors on Defense Meteorological Satellite Program (DMSP) satellites. During more than half of the 110 nights of JULIA operations in 1998 and 1999, backscatter was observed from plumes extending above the layer of bottomside spread *F.* On 98% of the nights with no plumes, the S_4 index measured at Ancon was <0.8. On ~90% nights with plumes, $S_4 > 0.8$. DMSP F14 crossed the magnetic equator within 7.5° longitude of Ancon near the 2100 local time (LT) meridian on 61 nights. During 32 overpasses, DMSP detected no equatorial plasma bubbles (EPBs), and JULIA detected no plumes. DMSP encountered EPBs on only 9 of the remaining 29 nights when JULIA observed plumes. Two plumes detected by JULIA on 15 April 1999 did not coincide with nearby EPBs crossed by the two satellites on the same evening. We also compared the seasonally averaged percent of nights with $S_4 \geq 0.8$ at Ancon with the percent of orbits in which a DMSP satellite detected EPBs. Data were accumulated between May 1994 and the first quarter of 2001. On a global scale at solar minimum, DMSP encountered very few EPBs. In years near solar maximum the two data sets were well correlated. However, there were more nights with $S_4 \geq 0.8$ at Ancon than EPB encounters by DMSP satellites. This discrepancy reflects the effects of different sampling intervals and the fact that about a third of the plumes fail to reach the DMSP altitude. Still, a correlation coefficient of 0.88 indicates that EPB detection at 840 km is a good indicator that scintillation activity is occurring near the spacecraft's longitude at the Earth's surface. The data also suggest that bubbles are often generated in bursts rather than at nearly uniform intervals. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2439 Ionosphere: Ionospheric irregularities; 2481 Ionosphere: Topside ionosphere; 1650 Global Change: Solar variability; 2499 Ionosphere: General or miscellaneous; *KEYWORDS:* equatorial ionosphere, irregularities, solar cycle variations

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1. Introduction

[2] Plasma turbulence at low magnetic latitudes in the postsunset ionosphere and its effects on the propagation of electromagnetic signals are well-studied topics (cf. review by *Aarons* [1993] and references therein). The most persistent effects include the phase and amplitude scintillation of transionospheric radio signals. *Rufenach* [1975] modeled effects of radio wave phase planes crossing thin Fresnel screens in the ionosphere. Ground observers sample diffraction patterns whose spectral characteristics are causally related to those of the Fresnel screen. *Balsley et al.* [1972] suggested that rapid recombination of ions and electrons after sunset rendered the bottomside of the *F* layer unstable to the growth of Rayleigh-Taylor (R-T) plasma turbulence. In the "local" approximation [*Kelley*, 1989] the linear growth rate for the generalized R-T instability is

$$\gamma \approx -\frac{\mathbf{g}'}{\nu_{in}} \cdot \frac{\nabla n}{n} - R \tag{1}$$

where n is the ambient plasma density, ν_{in} is the local ion-neutral collision frequency, and R is the recombination rate. The effective gravity $\mathbf{g}'$ [*Ott*, 1978] is given by

$$\mathbf{g}' = \mathbf{g} - \nu_{in} \cdot \frac{(\mathbf{E_0} \times \mathbf{B})}{B^2}, \tag{2}$$

where $\mathbf{g}$ is the acceleration due to gravity, $\mathbf{E_0}$ represents the background electric field, and $\mathbf{B}$ is the Earth's magnetic field. Since $\mathbf{g}$ and $\mathbf{B}$ are constant at a given location, growth rates of equatorial plasma bubbles (EPBs) are controlled by the variability of $\frac{\nabla n}{n}$, $\mathbf{E_0}$, and indirectly by the height of the *F* layer. Since $\mathbf{g}$ is downward, the region of positive γ is below the peak of the *F* layer. In an unpublished manuscript

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("Theory of equatorial spread F," preprint, Max Planck Inst. für Extraterr. Phys., 1973), G. Haerendel pointed out that since the R-T instability involves the interchange of entire flux tubes, the growth rate is controlled by the flux tube integrated, rather than local, Pedersen conductivity. This allows the ionosphere to be unstable on field lines on which the equatorial apex is at or above the peak of the *F* layer [*Sultan*, 1996]. However, for the limited goals of this brief report equation (1) has heuristic value.

[3] Detections of radar backscatter from strong plasma turbulence [*Woodman and LaHoz*, 1976] and of deep plasma depletions by satellites [*Burke et al.*, 1979] well above the peak of the *F* layer, where the sign of ∇n reverses, indicated that other processes were operating. *Scannapieco and Ossakow* [1976] followed the R-T instability into the nonlinear regime to show how EPBs propagate above the peak of the *F* layer. Equation (2) also indicates that the R-T growth rate increases substantially whenever an electric field with an eastward component is present in the equatorial ionosphere. *Tsunoda et al.* [1982] employed two radars on Kwajalein during overflights of the Atmosphere Explorer E (AE-E) satellite to specify the shapes of bubbles perpendicular to the local magnetic field. Plumes/bubbles appear to have elongated wedge-like shapes that extend upward from the bottomside source region into the topside ionosphere.

[4] Our ability to study spread *F* related phenomena has been enhanced by (1) the development of the Scintillation Decision Aid (SCINDA) system [*Groves et al.*, 1997] and (2) the commissioning of the Jicamarca unattended long-term studies of the ionosphere and atmosphere (JULIA) radar [*Hysell and Burcham*, 1998]. The first elements of SCINDA were installed near the dip equator at Ancon, Peru (11.79°S, 282.82°E, magnetic latitude 0.9°) and at Antofagasta, Chile (11°S magnetic latitude) to monitor 250 MHz signals from two geostationary satellites located to the east and west. The timing of signal scintillations reaching the antennas at Ancon and Antofagasta can be used to infer the zonal drifts and estimate the altitudes of causative plasma irregularities [*Valladares et al.*, 1996; *Groves et al.*, 1997]. SCINDA stations were recently installed at Ascension Island, Bahrain, Diego Garcia, and Guam.

[5] JULIA is a low-power, 50 MHz radar located at Jicamarca, Peru (11.96°S, 283.1°E) near Ancon. It is used to study the nightside ionosphere in extensive campaign-like operations. As such, it significantly extends the operational duty cycle of the full-powered Jicamarca incoherent scatter radar (ISR) [*Woodman and LaHoz*, 1976]. From JULIA backscatter, *Hysell and Burcham* [1998] showed that plasma irregularities form in the bottomside of the *F* layer almost nightly near equinoxes. Whether these irregularities evolve into plumes depends on several factors. *Hysell and Burcham* [1998, Table 1] indicate that plumes almost certainly form if by 2000 local time (LT) bottomside irregularities are present and the polarity of the electrojet has not reversed. *Aarons et al.* [1999, Figure 3b] show several examples of plume morphologies. On the night of 15–16 October 1996, plumes rose to heights of only ~400 km. During the main phase of a magnetic storm on 22–23 October 1996, plumes were detected continuously by JULIA from ~2100 to 0200 LT, and strong scintillations were measured in a continuous band from Easter Island to Ascension Island.

[6] The scale sizes of irregularities responsible for radar backscatter (a few meters at Jicamarca and a few centimeters at ALTAIR) and UHF scintillations (a few kilometers) are different. So, too, are the longitudinal scale sizes of EPBs. Satellites flying in low-inclination orbits regularly encounter multiple EPBs in the evening LT sector. Deep plasma depletions have typical east-west widths of 50 to 80 km [*Hanson and Bamgboye*, 1984]. *Hysell and Kelley* [1997] and *Chen et al.* [2001] analyzed high-resolution measurements of plasma densities and velocities within bubbles. Measured scale sizes extended from tens of kilometers to meters, spanning the longitudinal dimensions of bubbles down to those of plasma irregularities responsible for radio wave scintillation and radar backscatter.

[7] We have initiated two surveys of latitudinal plasma density profiles in the evening sector measured by sensors on polar-orbiting Defense Meteorological Satellite Program (DMSP) satellites. Deep density depletions, characteristic of EPBs, were frequently encountered. Our first DMSP-based study focused on the dependence of EPB detection on season and longitude and the levels of geomagnetic activity during 2 years near solar maximum [*Huang et al.*, 2001]. Generally, the seasonal/longitudinal distribution of EPBs sampled by DMSP satellites was in good agreement with predictions of a model proposed by *Tsunoda* [1985] and with ground-based observations of range spread *F* associated with radar plumes [*Aarons*, 1993]. *Huang et al.* [2001] also demonstrated that while most EPB detections occurred during periods of magnetic quiet, they were over-represented at times when $Kp \geq 5$. Intense EPBs were frequently detected during the initial and main phases of geomagnetic storms. However, they were absent for days during the recovery phase. The latter observation is attributed to the activation of a counter dynamo excited by stormtime Joule heating at auroral latitudes [*Scherliess and Fejer*, 1997; *Fejer and Scherliess*, 1997].

[8] A second study by *Huang et al.* [2002] analyzed more than 8300 EPBs detected during 75,000 DMSP equatorial crossings in the evening sector. The database covered a full solar cycle from 1989 through the first quarter of 2001. The analysis generally confirmed and extended solar maximum results. A ~0.98 correlation was found between the number of EPBs detected by DMSP in a given year and yearly averaged values of the $F_{10.7}$ index, demonstrating a controlling influence of solar activity. High correlations applied both on global and regional scales. During 4 solar minimum years we found that about one third of the EPBs were detected when traces of the Dst index versus time had significant negative slopes ($dDst/dt \leq -5$ nT/hr). Negative slopes in Dst traces indicate that the ring current was being energized and/or transported closer to the Earth [*Burke et al.*, 1998]. This requires electric field penetration of the inner magnetosphere earthward of the initial ring current location [*Burke et al.*, 1998, 2000]. In the ionosphere these electric fields are also responsible for the triggering of many EPBs.

[9] It is generally accepted that EPBs are related to radar plumes [*Tsunoda et al.*, 1982]. However, to the best of our knowledge, no quantitative statistical relationship between them has been reported. The large DMSP database allows us to address this issue. This paper summarizes results of direct comparisons between DMSP and ground-based

Table 1. JULIA Operations in 1998 and 1999

Year	Month	Observations	Plumes
1998	March	8	5
1998	April	6	6
1998	October	20	11
1999	January	12	2
1999	February	7	5
1999	March	4	2
1999	April	19	10
1999	June	7	0
1999	September	13	7
1999	October	11	3
1999	November	1	0
1999	December	2	2

observations made at the Ancon scintillation station and the JULIA radar installation. Data from Ancon are in the form of S_4 indices that measure the standard deviations of 250 MHz signals divided by the average signal intensity [*Briggs and Parkin*, 1963]. It is necessary to specify S_4 levels appropriate for comparison with EPB occurrence. In section 2 we briefly describe the different measurement techniques. We then compare Ancon measurements with those of the JULIA radar in 1998 and 1999 to show that when plumes penetrated to the topside, $S_4 \geq 0.8$. Finally, seasonal distributions of EPB detections by DMSP in the Ancon longitude sector were compared with $S_4 \geq 0.8$ episodes. Seasonal correlations between the two quantities over the last half of the present solar cycle are found to be quite good. The discussion section considers the significance of agreements and disagreements between the satellite and ground-based measurements.

2. Ground and Satellite Observations

[10] The 50 MHz JULIA radar uses the north and south quarters of the Jicamarca ISR to emit linearly polarized waves that propagate perpendicular to the Earth's magnetic field. The east and west quarters of the antenna act as receivers. JULIA is programmed to emit pulses of 26.6 μs duration at a repetition rate of 100 Hz. This allows sampling of 200 range gates of 4 km extent from 95 to ~900 km altitude [*Hysell and Burcham*, 1998]. Three UHF antennas aligned in the east-west direction were installed at Ancon in May 1994 to monitor 250 MHz signals from a geostationary satellite at ~260°E. The subionospheric intersection of the UHF ray is located northwest of Ancon.

[11] Plasma density measurements are available from multiple DMSP satellites flying in the evening LT sector during a full solar cycle from 1989 to 2001. DMSP satellites orbit the Earth in 98.7° inclined polar orbits at an altitude of ~840 km. Orbital planes are Sun-synchronous near the 0600–1800 or the 0900–2100 LT meridians. The plasma sensors on DMSP satellites are described by *Greenspan et al.* [1986]. We consider only plasma densities sampled in the evening sector as the spacecraft moved toward the northwest at low magnetic latitudes. The prime sector for detecting ionospheric irregularities at Ancon extends from 1930 to 2130 LT [*Valladares et al.*, 1996].

[12] With a period of ~104 min, DMSP satellites complete ~14 orbits per day. The longitudinal separation between ascending nodes is ~25°. For detailed comparison with Ancon and JULIA measurements we only consider data acquired during DMSP orbits that passed within 7.5° of the ground observatories. On average, 17 or 18 useful DMSP orbits are available per month. To reduce errors caused by low counting statistics we have grouped observations by season in bins centered on the June and December solstices and the two equinoxes. Data are presented as rates of EPB encounters normalized to the number of DMSP passes through the longitude bin.

[13] In 1998 and 1999 JULIA operated during 110 nights, listed by the number per month in Table 1. The table's right column indicates the number of plumes detected between 1930 and 2130 LT in given months. Clear seasonal differences appear in the data. Observations in 1998 were made near the equinoxes, when plumes were detected during 22 out of 34 nights (65%). A wider seasonal distribution was sampled in 1999. During solstice months the rate of plume detection was 4 out of 22 nights (18%). In the equinoctial months of 1999, JULIA detected plumes on 27 out of a possible 54 nights (50%). For comparison with DMSP observations, we note that on approximately one third of the nights when JULIA detected plumes, they failed to reach altitudes >600 km.

[14] Figure 1 provides an example of simultaneous JULIA and scintillation measurements made during the LT night of 14–15 April 1999. The top and bottom plots of Figure 1 give the intensity of the radar backscatter signals at Jicamarca and the S_4 indices from Ancon, respectively, plotted as functions of local time. The interval corresponds to universal time (UT) on 15 April 1999, since $LT = UT - 5$ at Ancon. JULIA measurements show that reflections from E layer altitudes persisted throughout the night. Starting at 1900 LT, reflections were detected from bottomside irregularities that slowly rose in altitude. Two plumes were observed first at ~2015 then at ~2040 LT. The S_4 trace in the lower plot of Figure 1 shows that scintillation activity began at ~1930 LT and increased to a sustained maximum near 0.8 at 2000 LT. Irregularities persisted above both observatories until ~2100 LT. Data in Figure 1 are consistent with the formation of plasma bubbles to the west of Ancon/Jicamarca before 2000 LT (0100 UT) drifting eastward across the radar's field of view. Attention is directed to intensified backscatter that appeared from 2218 to 2236 LT

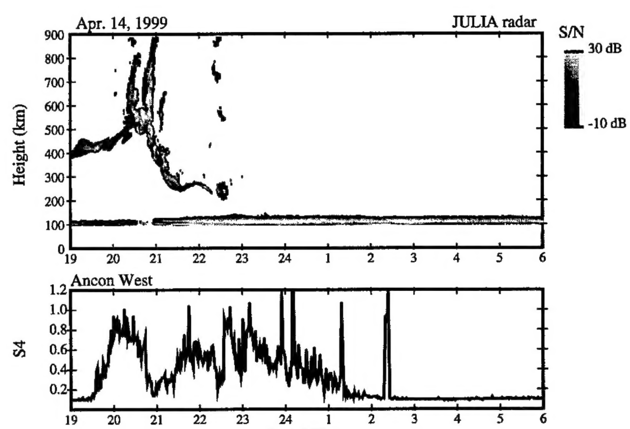

Figure 1. JULIA radar backscatter (top) and S_4 index for 250 MHz scintillations measured at Ancon (bottom) during the local time night of 14–15 April 1999.

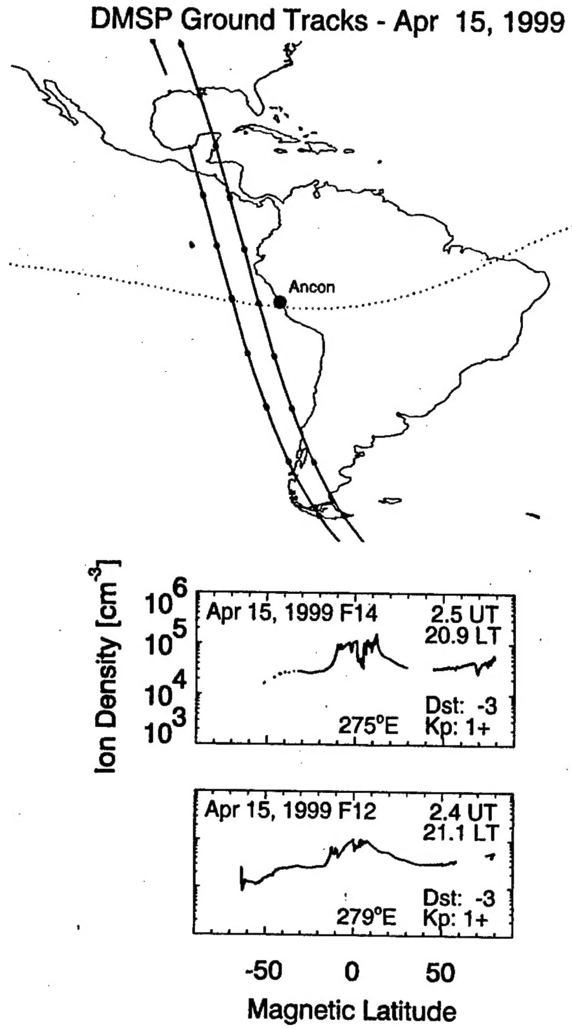

Figure 2. Plasma densities measured by DMSP F12 and F14 in the period covered in Figure 1 plotted as a function of magnetic latitude. The magnetic equatorial crossing for F12 occurred at ~0225 UT, 279°E and ~2107 LT. The F14 crossing was at ~0230 UT, 275°E and ~2054 LT. Markings on the DMSP trajectories are at intervals of 10° magnetic latitude.

(0318–0336 UT) at altitudes near 500, 700, and 850 km. These broken patches of irregularities were accompanied by decreased scintillation activity. Intense scintillations (S_4 > 0.8) resumed only when radar backscatter intensified from 2236 to 2248 LT (0336–0348 UT) from a patch of irregularities near 200 km.

[15] We have compared maximum values attained by the S_4 index for 250 MHz signals measured at Ancon with radar measurements during the 110 nights of JULIA operation. Data were first separated according to whether or not plumes were detected on a given night. On 56 of the 57 nights during which no plume activity was detected, S_4 < 0.8. Conversely, on 48 out of 53 nights when JULIA detected plumes $S_4 \geq 0.8$. On the five nights with plume activity and $S_4 < 0.8$, the plumes rose only to altitudes <600 km. On this empirical basis, we suggest that $S_4 \geq 0.8$, provides a useful "rule of thumb" for estimating, in the absence of JULIA data, when plumes or bubbles may be present in the ionosphere above Ancon.

[16] The times of onset for the increase in S_4 and the first plume in Figure 1 correspond to 0100 and 0120 UT, respectively. Their cessation occurred at 0200 UT on 15 April 1999. At 0225 and 0234 UT the DMSP F12 and F14 satellites crossed the magnetic equator in the evening sector at geographic longitudes of 295.5°E and 275.5°E, respectively. The top portion of Figure 2 shows the ground tracks of the two spacecraft moving to the northwest and crossing the magnetic equator ~3° and 7° to the west of Ancon. The bottom plots in Figure 2 show plasma densities measured by the DMSP satellites given as functions of magnetic latitude. To aid the comparison of plasma densities with satellite locations the trajectories are marked at intervals of 10° magnetic latitude. The plasma densities measured by both DMSP satellites manifest clear depletions near the magnetic equator, with smaller-scale structures nearby. Apex altitudes of field lines on which DMSP satellites encountered off-equatorial depletions are well above 840 km. Data presented below are normalized to the percent of orbits in which DMSP satellites encountered plasma bubbles. Even though Figure 2 shows that F12 and F14 crossed multiple EPBs, only a single orbit for each spacecraft is counted [*Huang et al.*, 2001]. During magnetically quiet times, plasma bubbles/plumes generally drift eastward [*Groves et al.*, 1997]. Clearly, the depletions traversed by the DMSP satellites do not correspond to the plumes observed by JULIA between 0100 and 0200 UT. One of them could possibly correspond to the plume remnants that drifted across the radar beam near 0330 UT. To move 3° or 7° in 1 hour, a plume/bubble would have to drift eastward at ~100 m/s or ~200 m/s. Such zonal drifts are attainable during periods when the solar flux at 10.7 cm is high [*Fejer et al.*, 1991].

[17] We have examined latitudinal plasma density profiles measured by the DMSP F14 satellite when it passed within 7.5° longitude of Ancon during the 110 nights of JULIA operation. Results of our survey, listed in Table 2, show that overpasses occurred on 61 nights. Neither bubbles nor plumes were detected on 32 of them. On 20 nights JULIA detected plumes but DMSP crossed no bubble. Both JULIA and DMSP detected plumes/bubbles on only 9 nights. In no case did DMSP encounter a bubble when JULIA failed to detect a plume. We defer comment on the significance of agreements and discrepancies between JULIA and DMSP measurements to the discussion section.

[18] We next apply our working hypothesis that plumes are identical to EPBs and our empirical rule that $S_4 \geq 0.8$ indicates periods of plume/bubble activity. Figure 3 compares DMSP detections of EPBs with scintillations observed at Ancon. Ancon and DMSP measurements were averaged by season starting when the station opened in 1994. Filled diamonds represent the percent of nights during a given season when $S_4 \geq 0.8$ while Ancon was in the 1930–2130 LT sector. Open circles represent the percent of orbits when a DMSP satellite encountered an EPB while crossing the

Table 2. Comparison of JULIA and DMSP Measurements

Year	JULIA	DMSP	Neither	Plume	Both
1998	34	20	6	11	3
1999	76	41	26	9	6

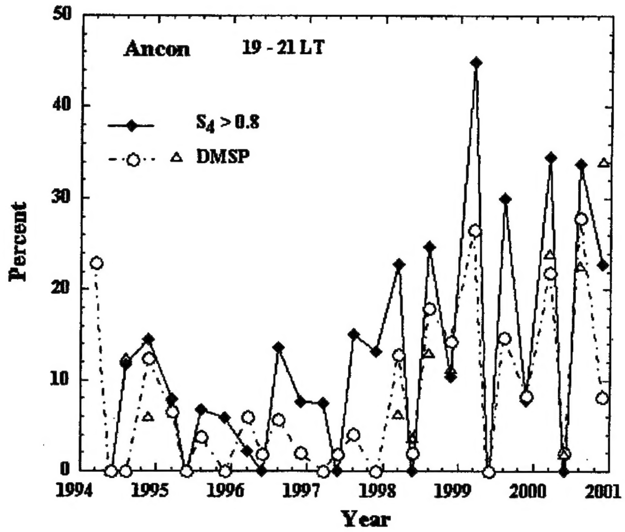

Figure 3. Seasonally averaged rate of EPB encounters by DMSP satellites in the Ancon longitude sector and seasonally averaged percent of nights with $S_4 \geq 0.8$ at Ancon plotted as functions of time from 1994 to 2001.

Ancon longitude sector. Open triangles indicate periods when more than one DMSP satellite collected data (cf. Table 1 of *Huang et al.* [2002]). Note that the orbital planes of all DMSP satellites used in this study were near the 2100 LT meridian. Attention is directed to three observational points. First, clear seasonal and solar cycle dependencies appear in both data sets. Second, except in the deepest part of solar minimum from 1996 through the first half of 1998, the seasonal distributions for both data sets are similar. During solar minimum the low rate of EPB encounters obscures meaningful seasonal statistics. Third, when two DMSP satellites were operating in a given year, their observations were generally in reasonable agreement.

[19] Seasonally averaged values of the rate of EPB encounters are plotted in Figure 4 as a function of the percent of nights at Ancon with $S_4 \geq 0.8$. All data points of Figure 3 are used. In the 1930–2130 LT sector the number of EPBs detected by DMSP was consistently lower than the number of intense scintillation events observed on the ground. However, the high correlation coefficient R = 0.88 indicates surprisingly good agreement overall between the two diverse sets of measurements. The slope and intercept suggest that when a DMSP satellite flew over Ancon when $S_4 \geq 0.8$, it had a ~60% probability of detecting an EPB. We have made a similar comparison of EPB encounters with $S_4 \geq 0.8$ events measured at Ancon in the 2130–2330 LT sector (not shown). However, the decreased regression coefficient of 0.81 is relatively high for a local time sector that DMSP orbits abutted but never entered.

3. Discussion

[20] In the previous sections we have compared multipoint measurements by the JULIA radar, the 250 MHz scintillation monitor at Ancon, and plasma detectors on DMSP satellites. Our comparison of JULIA and Ancon measurements established a practical discriminant, $S_4 \geq 0.8$, for estimating times when plumes/bubbles were present in the topside ionosphere above Peru. DMSP flew through the Ancon–Jicamarca longitude sector during 61 of the 110 nights of JULIA operation. DMSP crossed only 9 EPBs during the 29 nights when JULIA detected plumes. Our comparison of seasonally averaged rates of EPB encounters with $S_4 \geq 0.8$ episodes showed similar seasonal and solar cycle agreement. The correspondence was weak during solar minimum but improved as the solar cycle progressed toward maximum. Most likely the low rate for DMSP detecting EPBs during solar minimum reflects the low intensity of solar drivers of the F-layer dynamo [*Fejer et al.*, 1991]. The remainder of this section considers the significance of observed levels of agreement/disagreement between DMSP measurements and those at JULIA/Ancon.

[21] The first consideration concerns temporal and/or spatial biases caused by the relative locations of DMSP orbital planes and ground observatories. Data from the AE-E satellite indicate that typical longitudinal widths of EPBs are <1° [*Hanson and Bamgboye*, 1984]. The DMSP F14 orbital plane was close to the 2100 LT meridian. The longitude of Ancon (282.8°E) crosses this meridian at ~0210 UT. The longitude bin 290° to 275°E crosses the F14 orbital plane between 0140 and 0240 UT. This partially overlaps the Ancon sampling interval of 1930 to 2130 LT (0030 to 0230 UT). For simplicity we assume that bubbles encountered by DMSP are confined to ±15° magnetic latitude. DMSP satellites take ~9 min to cover this range. Within this time they move 7° in geographic longitude. With a declination of ~3° at Ancon, this translates to a span of ~10° in magnetic longitude. These space/time considerations make it seem improbable that a DMSP satellite would cross an isolated bubble that formed near the 2100 LT meridian within a given hour and percolated to altitudes ≥840 km.

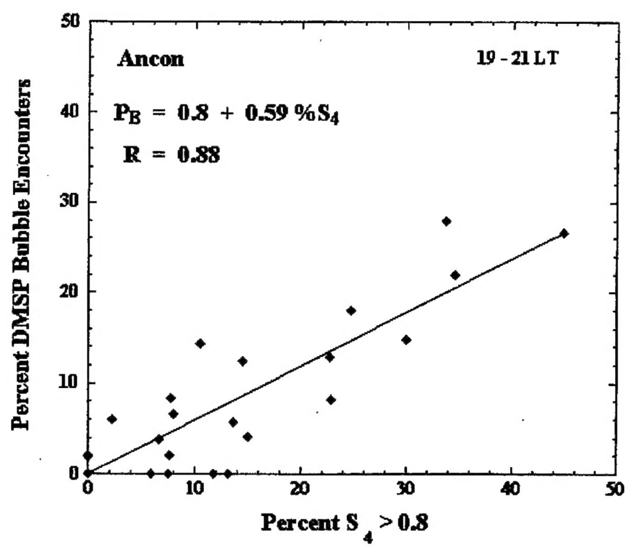

Figure 4. Scatterplot of rate of EPB encounters by DMSP satellites in the Ancon longitude sector plotted as a function of percent of nights with $S_4 \geq 0.8$ at Ancon. Scintillation measurements at Ancon were acquired between 1930 and 2130 LT.

[22] This low probability makes it understandable that DMSP sampled fewer EPBs than the JULIA radar detected plumes and the Ancon monitor observed $S_4 \geq 0.8$ scintillation levels. Examining JULIA backscatter data, one sees that a third of the plumes failed to reach DMSP altitudes. *Aarons et al.* [1999] reported on phenomena observed during the JULIA campaign of October 1996. Two examples are relevant to the present discussion. First, Figure 3a of *Aarons et al.* [1999] shows several plumes that rose to peak altitudes near 400 km. Within this period of low-altitude plumes, DMSP F12 flew through the Ancon longitude sector but detected no EPBs. Second, on the night of 22–23 October 1996, intense and widespread plume activity was observed in JULIA backscatter. *Aarons et al.* [1999, Figure 5a] show that plumes were present for more than 5 hours at all topside altitudes <900 km. This activity coincided with the main phase of a geomagnetic storm. Strong scintillations were observed from Easter Island across the South American continent to Ascension Island. DMSP F12 penetrated topside plasma depletions during four consecutive orbits, spanning more than 100° in longitude.

[23] Combined data from JULIA, Ancon, and DMSP suggest the following interpretation. DMSP satellites have the highest probability of encountering EPBs at times when multiple bubbles form and propagate to altitudes above 840 km. Isolated bubbles may form and reach DMSP altitudes but at times and places away from the satellite's equatorial crossings. Probabilities for encountering such EPBs are low. The examples presented in Figures 1 and 2 appear quite representative of EPB events observed by DMSP satellites. Figure 1 shows that beginning at ~0130, JULIA detected two different plumes that reached DMSP altitude. Less than an hour later DMSP F12 and F14 crossed multiple bubbles off the west coast of South America. This appears to be an isolated sequence of EPB activity that began and ended abruptly. One half hour before JULIA detected plume activity, the F12 and F14 satellites crossed the magnetic equator at 304° and 300°E, respectively. Neither spacecraft detected an EPB. The same was true during the two equatorial crossings by these spacecraft near 0415 UT.

[24] Geomagnetic activity was low throughout 15 April 1999, with Kp ranging between 1^+ and 0^+. Under these circumstances we believe that the thermospheric dynamo [*Eccles*, 1998] was the dominant source of eastward electric fields to drive the R-T instability. In the simplest scenario the dynamo creates a standing pattern of rising and falling plasma in the postsunset *F* layer. In this case, repeated patterns of rising and falling bottomside irregularities (Figure 1) would be detected by JULIA-like radars in Brazil and in the eastern Pacific. We also expect to see plumes excited near 2030 LT that propagate to DMSP altitude. This does not seem to be what happens. Rather it appears that on the night of 14–15 April 1999 dynamo electric fields generated to the east and west of Ancon were not strong enough for bottomside irregularities to grow into upward propagating plumes before the electric field reversal. The data suggest that quiet-time EPBs, reaching DMSP altitude, were generated in bursts that lasted for ~1 hour. A simple extension of the model proposed by *Eccles* [1998] would require that either the postsunset dynamo electric field or the height of the bottomside layer is modulated above and below critical threshold levels. In the latter case, equation (1) suggests a central role for damping caused by ion-neutral collisions. To first approximation, ν_{in} decreases exponentially with altitude. The overall effect is to extend the time required for bottomside irregularities to grow into bubbles.

4. Summary and Conclusions

[25] This brief report examined relationships between measurements of the JULIA radar, the Ancon scintillation monitor, and plasma density sensors on DMSP satellites. During less than half of the 110 nights of operation, JULIA detected backscatter from plumes of plasma irregularities rising above the layer of bottomside irregularities. Most plumes were observed near the two equinoxes. About a third of the plumes failed to reach altitudes >600 km. On 98% of the nights with no plumes, the S_4 index measured at Ancon was <0.8. Conversely, on ~90% of the nights with plumes S_4 > 0.8. DMSP F14 crossed the magnetic equator in the 275°–290° longitude bin near the 2100 LT meridian on 61 of these nights. DMSP encountered bubbles on only 9 of the 29 nights when JULIA observed plumes. Plumes detected by JULIA on 14–15 April 1999 did not coincide with EPBs crossed by the DMSP F12 and 14 satellites.

[26] Seasonally averaged rates of nights with $S_4 \geq 0.8$ at Ancon between 1930 and 2130 LT were compared with similarly averaged percents of orbits in which a DMSP satellite detected EPBs. Figures 3 and 4 show that except at solar minimum when the global rate of EPB encounters by DMSP satellites was low [*Huang et al.*, 2002] the two quantities were well correlated. However, it is clear that there were more nights at Ancon when $S_4 \geq 0.8$ than when DMSP satellites crossed EPBs in the 275°–290° longitude bin. This discrepancy reflects two factors. First, the sampling interval at Ancon was 2 hours, while DMSP spends only 9 min between −15° and +15° magnetic latitude. Second, many ionospheric disturbances that drive $S_4 \geq$ 0.8 scintillations fail to reach the altitude of DMSP. Still, the 0.88 correlation coefficient indicates that detections of EPBs at 840 km are good indicators of scintillation activity at subsatellite longitudes. Further, we have shown that many EPBs occur over the vast expanses of oceans where no ground monitors are present. In fact, EPB occurrence peaks in the mid-Atlantic in the vicinity of the anomaly. This is of practical significance. Having shown the relation between space- and ground-based observations of EPBs we feel confident in proceeding with our analysis which will combine these complementary measurement techniques.

[27] We also considered implications of the brief intervals spent by DMSP satellites crossing low (~±15°) magnetic latitudes and the <1° longitude widths of EPBs [*Hanson and Bamgboye*, 1984]. It appears improbable that a DMSP satellite would cross a single plume/bubble generated near 2100 LT even if it propagated to altitudes >840 km. The fact that DMSP regularly encounters EPBs suggests that multiple bubbles are generated in relatively brief intervals. This contention is supported by observations on 15 April 1999, when JULIA detected two plumes, and both F12 and F14 detected more than one bubble. In fact, more than one plume drifted across the JULIA radar beam between 1930 and 2130 LT on 45 of the 53 (85%) nights when plumes were observed. Our practice of only counting orbits during which EPBs were observed [*Huang et al.*, 2001] precludes

specifying the fraction in which more than one depletion was crossed. Experience suggests that the fraction is large. We conclude from the 15 April 1999 event that bubbles are normally generated in multiples and that our DMSP observations represent a lower limit to the true numbers generated. This is also suggested by the scintillation measurements made at Ancon (see Figure 1, from 1930 to 2100 LT) which show extended periods during which the S4 index remains high. The bursty nature of the generation mechanism must be considered in models for triggering of EPBs.

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